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Humidity

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Humidity is, together with temperature and pressure, one of the fundamental variables that characterize the local state of the atmosphere. Within the realm of agriculture, humidity measurements have a wide variety of applications, including prediction of plant diseases, prediction and maintenance of livestock comfort levels, estimation of evapotranspiration, and planning of hay and grain harvests. In micrometeorology, measurements of temporal and spatial gradients in humidity are used to infer fluxes of water vapor between surface and atmosphere. The requirements for these various applications can be quite different, so the choice of an appropriate measurement method or instrument necessitates some understanding of the underlying principles.

Air contains a large and variable array of constituents, but for many purposes it can be treated as a two-component mixture of water vapor and dry air, each of which behaves as an ideal gas, obeying its own equation of state and contributing in additive fashion to the total temperature and pressure of the moist air mixture. Vapor pressure, e, and vapor density, ρ_v, are thus related to each other and to absolute temperature, T, by a gas law,

$$e = \frac{\rho_v R_a T}{0.622} \qquad [1]$$

where R_a is a specific gas constant for dry air (287 J kg^{-1} K^{-1}), and 0.622 is the mole ratio of water vapor to dry air. In a closed system containing liquid water and air, the liquid and gas phases of water will reach an equilibrium described by the Clausius-Clapeyron equation. The vapor pressure under such conditions is the saturation vapor pressure, e_s. It has a temperature dependence that has been approximated numerically in various forms (Brutsaert, 1984). The Goff-Gratsch (1946) equation is considered the most accurate, and served as the basis for the Smithsonian Meteorological Tables of saturation vapor pressure (List, 1951). Other formulations are computationally simpler, with negligible sacrifice of accuracy. Eq. [2], developed by Richards (1971), is one example:

$$e_s = 1013.25\exp(13.3185t_r - 1.976t_r^2 - 0.6445t_r^3 - 0.1299t_r^4) \qquad [2]$$

$$\text{where } t_r = 1 - \frac{373.15}{T} \qquad [3]$$

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The humidity status of air also can be expressed on a mass basis. The mass of water vapor per unit mass of dry air is known as the mixing ratio, *m*:

$$m = \frac{m_w}{m_a} \qquad [4]$$

The most common expression of the moisture status of air, the relative humidity (RH), is the ambient mixing ratio divided by the mixing ratio of saturated air, *at the same temperature and pressure*, multiplied by 100:

$$RH = 100\frac{m}{m_s} \qquad [5]$$

To a very close approximation, m/m_s can be replaced in Eq. [5] by e/e_s.

A plot of Eq. [2] serves as the upper bound for what is commonly known as a psychrometric chart, a version of which is shown in Fig. 2–1. Below 0°C there is an additional parameter to consider, the saturation vapor pressure over ice, e_i. At the triple point of water (0.01°C and total pressure of 0.61 kPa) e_i and e_s are equal, but as temperature is further lowered e_i decreases faster than e_s. Relative humidity is always referenced to e_s, the saturation vapor pressure over water (supercooled water in the case of $T < 0$°C), meaning that air in equilibrium with

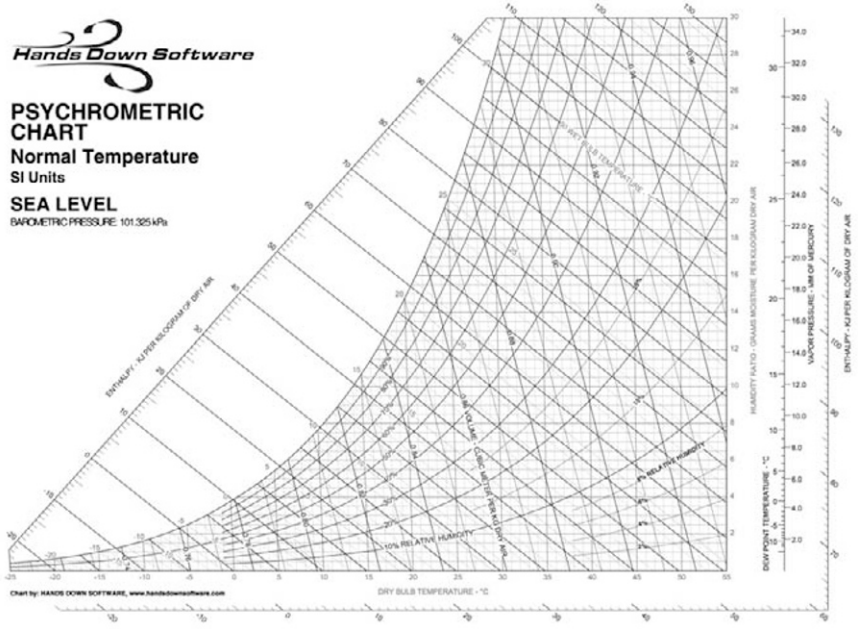

Fig. 2–1. Psychrometric Chart. (Provided courtesy of Hands Down Software, Edmond, OK).

ice will always have an RH below 100% (Fig. 2–2). This fact can actually be used to calibrate RH sensors at the "wet" end, by enclosing them in containers with ice and measuring their output at a series of controlled, sub-zero temperatures.

There are no methods available to directly measure mixing ratio or vapor pressure. Vapor density can be measured by optical means, but such instruments are too expensive for many applications. Consequently, determination of humidity has historically consisted of indirect temperature measurements that make use of the psychrometric relationships in Fig. 2–1 to derive vapor pressure or vapor density. For most purposes it is more convenient to use equations rather than charts to convert to the desired variable. An extensive list of such expressions is provided in the appendix of Ham (2005, this volume).

WET BULB PSYCHROMETRY

If a bulb is kept wet and the surrounding air is not saturated, it will exchange mass (water) and energy with its surroundings, and its equilibrium temperature, T_w, can be used to determine the ambient humidity:

$$[e_s(T_w) - e]/P = A[T - T_w] \quad [6]$$

The psychrometer coefficient, A, encompasses the ratio of coefficients for convective (sensible) and vapor (latent) transfer, modified by factors that account

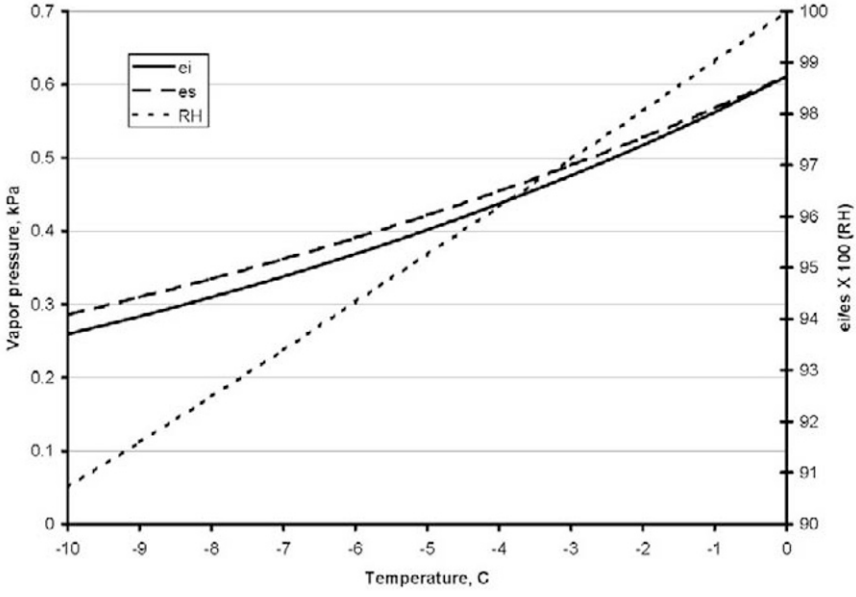

Fig. 2–2. Temperature dependence of saturation vapor pressures over ice and supercooled water at temperatures below 0°C, and corresponding "saturation" RH.

for radiative exchange and a molecular-kinetic resistance to evaporation (Wylie, 1985):

$$A = \frac{k_h}{k_v} f_v f_e \qquad [7]$$

The ratio k_h/k_v is sometimes referred to as the *psychrometric constant* in derivations that treat the wet bulb temperature as the temperature of adiabatic saturation. The corrections embodied in f_r and f_e are shown by Wylie to exceed unity by approximately 0.05 and 0.01, respectively. Exact calculation of A is nontrivial, because it depends on temperature, humidity, pressure, air stream velocity, and the dimensions of the wet bulb. In practice, it is determined empirically for a specified flow and system geometry at a given temperature, humidity, and pressure. For highest accuracy, corrections must be applied under other conditions, which necessitates iteration. If lesser absolute accuracy is sufficient, the readily calculated psychrometric constant, γ, can be used in place of the psychrometer coefficient where

$$\gamma = \frac{C_p}{0.622\lambda} \qquad [8]$$

Psychrometers consist of paired, ventilated temperature sensors, one of which is wet. The other sensor, known as the dry bulb, provides T. Manual instruments for wet/dry bulb measurements include sling psychrometers, in which the ventilation is accomplished manually by whirling the thermometers, and battery powered psychrometers that contain a fan to maintain a constant air flow across the wet bulb. In both cases, the wet bulb consists of a wick that is pulled over the bulb of one thermometer and wetted with distilled water. Longer-term, automated measurements can be made with thermocouples or thermistors connected to dataloggers. The sensors must be shielded from solar radiation, and provision must be made to keep the wet bulb wick wet by connecting it to a reservoir of water. Ventilation is provided with a fan. Such devices require relatively frequent attention, to refill the reservoir when necessary and to replace the wick, which is subject to contamination by dust and microbial growth. There is at least one commercial source for such instruments, and several literature sources with various designs for do-it-yourself construction, e.g., Allen et al. (1994); Ueda et al. (1991); and Mitchell et al. (1973). The method lends itself to specialized applications, and custom psychrometers have been used to measure humidity in insect microhabitats (Ferro & Chapman, 1980), livestock buildings (Mousley & Fryer, 1976), and broiler houses (Costello et al., 1991).

DEW POINT HYGROMETRY

If a surface in contact with air is cooled, eventually it will reach a point where net condensation will exceed net evaporation, and dew will form on it. The

temperature at which dew just begins to form is the dew point temperature, T_d, and knowledge of T_d is sufficient to determine vapor pressure using Eq. [2].

The objective of dew point hygrometry is thus to control the temperature of a surface such that it is at the dew point of an air stream moving past it. This is accomplished with a mirror coupled to an electrical circuit capable of both heating and cooling. A beam of light is aimed at the mirror so that its reflection strikes a photodetector. The mirror is cooled until dew forms, at which time the photocell detects a decrease in light intensity. This triggers heating until the dew is driven off. With appropriate control algorithms such a system can maintain the temperature of the mirror at exactly the point where dew begins collecting, which is T_d. The temperature is measured with a resistance temperature device (RTD).

The bane of dew point hygrometry is contamination of the mirror. Dust, salts, or any other impurities can cause the control system to maintain the mirror at an incorrect temperature. For this reason dew point hygrometers are not usually exposed to the free atmosphere. Instead they are installed in closed systems where ambient air is pulled through a filter prior to passing over the mirror. Even then, accuracy decreases with time due to mirror contamination. Manufacturers of commercial dew point hygrometers have devised methods for circumventing this difficulty. In one approach, the mirror is periodically heated to dryness to determine shifts in baseline reflectance. Another system makes no attempt to control mirror temperature at the dew point, instead operating in a transient mode by repeatedly passing through the dew point in heating and cooling loops. The dew point is then determined indirectly from changes in the time derivative of the mirror temperature. Because the mirrors in such systems are not continually wet they do not accumulate contaminants as quickly, but they also are not as accurate, and have not found widespread use (Wiederhold, 1997). Any dew point hygrometer, regardless of its design, performs better if the mirror is periodically cleaned. Under such conditions, dew point hygrometers can provide accuracy sufficient to calibrate other, less direct methods humidity instruments.

VAPOR DENSITY

The water vapor molecule has structural properties that cause it to absorb radiation at specific wavelengths throughout the solar spectrum (Goody & Yung, 1989; Kyle, 1991). Direct measurements of vapor density are based on this optical absorption in certain, well-defined spectral regions. At least two types of commercially available hygrometers make use of absorption within the ultraviolet (UV) portion of the spectrum. Each contains both a source and a detector of UV radiation, with the area between them open to the atmosphere. Extinction of the radiation emitted by the source depends upon the concentration of water vapor within the path. Ideally, if no other absorbing gases are present, this follows Beer's Law so that:

$$\ln\left(\frac{I}{I_o}\right) \propto \rho_v \qquad [9]$$

where I is the radiation reaching the detector when ambient vapor density is ρ_v, and I_0 is the radiation reaching the detector when ρ_v is nil. Unfortunately, changes in UV source strength and in transmissivity of the source and detector windows cause I_0 to drift, so that UV hygrometers are not well-suited for routine monitoring of *absolute* humidity. The strengths of UV hygrometers are rapid dynamic response to *relative* fluctuations in vapor density, and a finite, well-defined measurement volume. Consequently, both types of UV hygrometers find their primary application in eddy covariance flux measurements.

One instrument of this type, the Lyman-alpha hygrometer (Buck, 1976), uses a source in which hydrogen atoms are excited. As they return to ground state they emit radiation at 121.56 nm. Water vapor strongly absorbs at this wavelength, while other common atmospheric constituents do not. The detector in the Lyman-alpha hygrometer uses a photo ionization chamber, in which a pair of electrodes is suspended within an ionizing gas. The window of the detector is made of magnesium fluoride, which has a transparency window from 115 to 132 nm. Incident radiation ionizes the gas, inducing a proportional current. Lyman-alpha hygrometers have high sensitivity, but the source tubes have a limited lifespan and must be periodically replaced, due to leakage of the hydrogen and subsequent loss of source strength.

The second instrument of this sort, the krypton hygrometer, avoids the problem of short source lifetime by using a source that is filled with krypton gas rather than hydrogen (Campbell & Tanner, 1985). Krypton has a much lower diffusivity and hence is less prone to leakage, but its emission characteristics are not so ideal. It has emission lines at 116 and 123 nm, wavelengths at which O_2 absorption is nontrivial. Hence changes in ambient O_2 concentration, which can be caused by either pressure or temperature changes, will affect the measurement. Campell and Tanner (1985) showed that changes due to pressure should be sufficiently small that they can be ignored, but that temperature-induced changes were more serious. In particular, in eddy covariance applications, sensible heat transport will cause O_2 fluctuations that are correlated with vertical wind speed, introducing errors in the apparent latent heat flux unless corrections are made. Vapor density can be obtained from detector output voltage, V, as:

$$\rho_v = \frac{\ln V}{-xk_w} - \frac{\ln V_0}{-xk_w} + \frac{k_O}{-k_w}\rho_O \qquad [10]$$

where V_0 is the detector output in the absence of any absorber, x is the pathlength, k_w and k_0 are the absorption coefficients for water vapor and O_2, and ρ_0 is the density of O_2 (Campbell Scientific, 1995). The instrument is not generally used for absolute measurement, but rather for measuring fluctuations in ρ_v, pursuant to the determination of evaporation rate by eddy covariance:

$$E = \frac{\overline{w'(\ln v)'}}{-xk_w} - \frac{-k_O C_O M_O P}{-k_w RT^2}\left(\overline{w'T'}\right) \qquad [11]$$

The second term on the right is the correction for O_2 effects due to sensible heat transport, in which C_O is the mean concentration of O_2 (mol mol^{-1}) and M_O is the mole weight of O_2.

Infrared gas analyzers (IRGA) make use of relatively strong absorption bands by water vapor within the infrared portion of the spectrum. Infrared gas analyzers are not usually used for routine measurements of ambient humidity because they are expensive, but they have found widespread use for flux measurements due to their accuracy and rapid dynamic response. Such analyzers can simultaneously measure CO_2 density, taking advantage of the fact that CO_2 also has absorption bands in this region. This is accomplished by using a broadband source of IR radiation, maintained at a constant radiative temperature, and separate detectors fitted with band-pass filters. One common IRGA uses the 2.59 μm band for water vapor and the 4.26 μm band for CO_2. Since water vapor is typically present in much greater concentrations than CO_2, the CO_2 measurements must be corrected for H_2O interference due to pressure broadening and dilution, but correction in the other direction is unnecessary. Welles and McDermitt (2005, this volume) provide a much more detailed description of infrared gas analysis. They focus on CO_2, but the general operating principles apply to water vapor measurement as well.

Infrared gas analyzers have traditionally been closed-path instruments, in which the air of interest is pumped via tubing through the sample cell of the analyzer. This imposes some operational constraints. Condensation can occur within a sample line if its temperature at any point is lower than the dew point of the sampled air. This can be prevented by insulating the tubing or by heating it, although the latter changes the density of the air, so that the measured vapor density must be corrected to obtain the true vapor density. A more difficult problem is that caused by the tendency of water to adsorb to surfaces. Sample lines with high affinity for water vapor affect dynamic response by acting as hydraulic capacitors, damping fluctuations by adsorbing and desorbing water. Nearly all surfaces are imperfect in this regard, but some are much better than others. Tubing manufacturers and suppliers rate their products for water vapor adsorption. These ratings should obviously be considered in system design, but even more importantly, sample lines should be kept as short as possible and as clean as possible. The latter is best accomplished by frequent replacement of tubing and by the use of an appropriate filter at the sample inlet, a mandatory practice when using closed-path IRGAs.

To avoid the difficulties associated with closed path IRGAs, Auble and Meyers (1992) developed an open path analyzer that has been widely employed for flux measurements (e.g., Meyers, 2001), and at least one other open path design has since been developed and is now commercially available (LICOR, Lincoln, NE). The Licor open path IRGA approximates absorptance due to water vapor as:

$$\alpha = 1 - \frac{I_w}{I_0} \qquad [12]$$

in which I_w is the radiant power received at the detector in a wavelength where water vapor absorbs, and I_0 is the radiant power received in a nonabsorbing wavelength. A common source is used, with a chopper wheel in front that contains band-pass filters for water vapor, CO_2, and the nonabsorbing waveband. Open-path IRGAs are robust and simple to use, requiring less maintenance than closed-

path instruments, and initial experiences suggest that their calibrations are more stable against drift than those of closed-path IRGAs.

RELATIVE HUMIDITY

Relative humidity is the most common humidity measurement made, and there is a broad array of commercial RH sensors available from a variety of sources. In general they measure an electrical or mechanical property of a substrate that reversibly absorbs water as ambient relative humidity increases. Many materials expand and contract with changes in relative humidity, and this property has long been used as a basis for measurement. Substances that have been used include human hair, wool, cotton, and polymers, which are attached to mechanical or electrical transducers to record changes in humidity. Such instruments are susceptible to hysteresis and drift, but are relatively inexpensive.

In recent years the development of new, thin-film polymer substrates has provided sensors with much improved accuracy, dynamic response, and long-term stability. These have largely superseded the older, less accurate electromechanical devices. The two broad types of thin-film, electronic RH instruments in current use are resistance sensors and capacitance sensors. Wiederhold (1997) describes the construction, advantages, and disadvantages of each, and concludes that capacitive sensors exhibit faster response, better linearity, a lower temperature dependence, and better performance at low relative humidities. Commercially available capacitive sensors have specified accuracy of ±1% RH and drift of <1% RH per year. While the temperature dependence of the newest RH sensors is much less than in older instruments, it is still necessary to install them within radiation shields to minimize errors associated with radiant heating. A number of such sensors are provided with integral temperature sensors so that they can provide both air temperature and relative humidity, facilitating determination of vapor pressure. These sensors are used to monitor temperature and RH in a wide variety of applications, including greenhouse control, routine weather data collection, ET estimation and disease prediction. They also now have sufficient accuracy and dynamic response to be used in Bowen ratio applications (Fritschen & Fritschen, 2005, this volume).

Relative humidity sensors offer advantages over some other humidity methods at times when the vapor pressure drops below 0.61 kPa, the saturation vapor pressure at 0°C. Under such conditions, conventional dew point hygrometers behave unpredictably (Wiederhold, 1997). They may initially control mirror temperature at the dew point, but this is a metastable condition that may be optically indistinguishable from the frost point. Newly available dew point hygrometers that use surface acoustic wave detection reportedly can distinguish between dew and frost formation. Wet bulb psychrometers have obvious problems (freezing of the wick) under such conditions as well; however, we have measured RH with a capacitive RH probe above ice across a range of temperatures, and the calculated vapor pressures are essentially indistinguishable from the tabled values for saturation vapor pressure over ice, indicating acceptable accuracy.

The robustness of thin-film RH sensors is, paradoxically, their weakness. Since they require no routine maintenance there is a tendency to ignore them as

long as they produce plausible numbers. While it is true that the calibration drift for newer RH sensors is generally much less than for earlier models, it is not wise to assume continued accuracy without the mantle of proof afforded by periodic calibration.

CALIBRATION OF HUMIDITY SENSORS

Periodic assessment of accuracy is a consideration with any measurement device, no less so with humidity sensors. There are a number of possible options, varying in cost, convenience, and confidence level. Several manufacturers offer dew point generators, which, as their name indicates, can generate an air stream at a specified dew point. They work by bubbling dry air through deionized water that is controlled at the desired (dew point) temperature. The exiting air, which can be fed to the instrument to be calibrated, is saturated at the set point temperature, so its vapor pressure *in the dew point generator* can be calculated from Eq. [2]. If the total pressure at the instrument is different from that within the dew point generator, a correction must be applied:

$$e = \frac{P}{P_d} e_d \qquad [13]$$

where e and P are the vapor pressure and temperature at the sensor and e_d and P_d are the corresponding values at the bubbler within the dew point generator.

As an alternative to the dew point generator, a dew point hygrometer can be used as a secondary standard for calibrating other humidity sensors. Such an instrument should have an NBS-traceable calibration and should be dedicated to calibration, i.e., stored in a clean, dry environment and not used for other purposes. Relative humidity sensors also can be calibrated by suspending them in a closed container above saturated salt solutions for which the corresponding relative humidities are known (Table 2–1). For most salts the temperature dependence of RH is small, so control to the nearest degree or two is probably sufficient.

CONCLUDING REMARKS

Measurement of atmospheric humidity is so important to so many problems that there is a huge body of literature on the subject, and it is impossible to

Table 2–1. Relative humidities of saturated salt solutions at 20°C.

Lithium chloride	11.3
Magnesium chloride	33.1
Potassium carbonate	43.2
Sodium bromide	59.1
Sodium chloride	75.7
Potassium chloride	85.1
Potassium sulfate	97.6

cover all aspects of the topic in a survey chapter. The focus, therefore has been on a presentation of the methods commonly used in agricultural meteorology. Among the general conclusions:

1. For routine monitoring of humidity, as in weather stations, capacitive relative humidity sensors are probably the best choice. They are inexpensive, stable, and sufficiently accurate for most purposes.
2. For flux measurements, particularly eddy covariance, infrared gas analysis has the desirable characteristics of rapid dynamic response and high resolution (sensitivity to small fluctuations).
3. Dew point hygrometers are a good choice for applications where absolute accuracy is important and a clean, closed airstream can be provided to the instrument, e.g., in laboratory and growth chamber experiments, and in some field situations, such as Bowen ratio systems.
4. The principal attribute of wet/dry bulb psychrometry is that it can be done in a wide variety of ways with systems that can be constructed by the user to fit a particular need.
5. Regardless of the method chosen, cleanliness and frequent calibration checks will reap benefits that justify their time and trouble.

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